Dynamic Modeling and Ground Test of Tethered-net

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Abstract. Flexible tethered-net, a new kind of structure for advanced concepts in space exploration, has special potential application such as capturing space debris and building huge antenna. A critical issue in the design and analysis of space net system is deployment of modelling technology. The dynamics behaviour of flexible net systems is investigated based on finite segment approach in this paper. The flexible net is modelled as a series of collected semi-damp springs with masses lumped at appropriated nodes. Besides, a comprehensive study on a model for the tethered-net based on absolute nodal coordinates formulation (ANCF) is provided. Simulations show that the results based on the ANCF modelling method present a good agreement with that based on the conventional semi-spring damper modelling method. Then the flexible multibody dynamics models has been verified by comparison with ground experiment.

1 Introduction

NASA and ESA studies have shown that active measures must be taken to clear at least 5 to 10 space debris per year in order to maintain long-term stability of the space environment and the sustainable use of space resources [1-4]. This requires us to take steps to mitigate the possibility of impacts.

With progress in space science and technology, growing attentions had paid to flexible net system. In 2001, ESA proposed the ROGER (RObotic GEostationary orbit Restorer) project [5-7] to capture GEO abandoned satellites with a tethered flight. NASA-supported MXER (Momentum eXchange / Electrodynamic Reboost) project [8] envisioned the use of tether systems to provide propellant without propulsion. EDD (ElectroDynamic Debris Eliminator) [9] project of the United States DARPA project plans to launch 12 spacecraft, each carrying 200 electromagnetic networks, which can be used for cleanup of LEO space debris. The idea of using a spaceflight to construct a large spatial structure is derived from the concept of Furoshiki satellite system proposed by Nakasuka et al. [10], and in order to verify the Furoshiki satellite system, Japan's University of Tokyo and Kobe University conducted the first Furoshiki test in 2006 using the sounding rocket S-310-36 [11-13].

A lot of efforts have been made in the field of flexible nets dynamics. Hobbs et al [14] analyzed the influence that different structure within the rope do to the elastic and fatigue fracture properties. Etter et al.[15] studied the dynamic characteristics of the Kevlar rope under low frequency longitudinal vibration. It was found that the elastic modulus of the rope during dynamic

loading was much higher than that in the static case. The damping coefficient is higher than the damping coefficient when the vibration is small. Nishinari et al. [16] established a discrete dynamic model of extensible ropes, which considered the bending and elongation of the rope.

Chen Qin, Yang Leping et al.[17] systematically designed the space rope netting system, established the rigid and flexible coupling dynamic model of the space rope system by using the mass method, and studied the dynamics of the rope launching process. Problem, a number of ground rope tether ground tests were carried out, and the simulation model was verified by ground test. Through the rope tether ground test, Zhang Qingbin et al[18] checked and improved the space rope dynamic model. Gao Xinglong[19] used the LS-DYNA software to simulate the collision process of the space flight capture target. Yang Fang [20] studied the kinetics of the launch of the space rope based on the semi-mass damping spring model, and carried out the relevant experimental study. Liu[21] et al. have provided a modeling method for tethered-net based on ANCF. Minghe Shan[22] et al analyzed the influence by the initial deployment conditions with ANCF. From the above literature we can find that, there is no particularly perfect and efficient model to simulate the movement of the rope. And, what is more, experimental studies are more rarely.

Therefore, a discrete lumped mass model and a continuous absolute node coordinate model with aerodynamic are established in this paper. Through simulation and experiment analysis, it is found that both models can finely simulate the tethered-net. And ANCF model can show more details of the ropes, but meanwhile computationally expensive.

2 ANCF model

In ANCF, which is initially proposed by Shabana and utilized in solving large displacement and deformation problems, absolute positions and the gradients of the positions act as the element nodal coordinates to describe the configuration of a flexible system. As shown in Fig 1, the nodal coordinates of the elements are defined in a global inertial coordinate frame $(O_0, e_1^{(0)}, e_2^{(0)}, e_3^{(0)})$.

Figure 1. ANCF model.

The vector of arbitrary point P in three-dimensional element ij is $\frac{1}{r}$. And the derivative of $\frac{1}{r}$ with respect to the arc of the center of the beam is $\frac{1}{e_t} = \frac{\partial \frac{1}{r}}{\partial s}$, which is

$$\begin{aligned} \frac{1}{r^{(0)}} &= (X \ Y \ Z)^T \\ \frac{1}{e_t^{(0)}} &= (\partial X / \partial s \ \partial Y / \partial s \ \partial Z / \partial s)^T \end{aligned} \quad (1)$$

After deformation, the displacement field of point P in $(O_0, e_1^{(0)}, e_2^{(0)}, e_3^{(0)})$ is approximately described as follow by polynomial approximation.

$$\left. \begin{aligned} X &= a_1 + a_2 s + a_3 s^2 + a_4 s^3 \\ Y &= a_5 + a_6 s + a_7 s^2 + a_8 s^3 \\ Z &= a_9 + a_{10} s + a_{11} s^2 + a_{12} s^3 \\ \partial X / \partial s &= a_2 + 2a_3 s + 3a_4 s^2 \\ \partial Y / \partial s &= a_6 + 2a_7 s + 3a_8 s^2 \\ \partial Z / \partial s &= a_{10} + 2a_{11} s + 3a_{12} s^2 \end{aligned} \right\} \quad (2)$$

So $\frac{1}{r^{(0)}}$ and $\frac{1}{e_t^{(0)}}$ in formula (1) can be expressed as

$$\frac{1}{r^{(0)}} = Q_r A, \quad \frac{1}{e_t^{(0)}} = Q_t A \quad (3)$$

where A is the coefficient matrix. Q_r and Q_t are 2×8 matrices.

We can assemble $\frac{1}{r}$ and $\frac{1}{e_t}$ into matrix W to represent the configuration of P . After observing formula (3), matrix W becomes

$$W = \begin{pmatrix} \frac{1}{r}^T & \frac{1}{e_t}^T \end{pmatrix} = QA \quad (4)$$

where $Q = (Q_r, Q_t)^T$. Though analysis, we can get that the vector $\frac{1}{r}$ can be represented by the absolute node coordinates as

$$\frac{1}{r^{(0)}} = Q_r Q^{-1} W = NW \quad (5)$$

where N is the shape function.

The virtual work of the inertial force in the unit is

$$\delta P_a = -\rho \int_0^l \ddot{\mathbf{r}}^T \delta \dot{\mathbf{r}} ds \quad (6)$$

where ρ_l is the unit length quality of the element. Substituting Eqs.5 into Eqs.6 leads to

$$\delta P_a = -\ddot{W}^T M \delta \dot{W} \quad (7)$$

where $M = \rho \int_0^l N^T N ds$.

The unit's deformation virtual work consists of two parts, which are virtual work of bending and elastic force. Therefor

$$\delta P_s = -\frac{\partial (U_d + U_b)}{\partial W} \delta \dot{W} \quad (8)$$

where U_b is the bending energy and U_d is the elastic energy. And after analysis, we have got

$$\delta P_s = -KW \delta \dot{W} \quad (9)$$

where $K = \int_0^l EA \left[3W^T (N_s^T N_s)^2 W^T - N_s^T N_s \right] ds$.

The extral forces that acting on arbitrary element ij in the ground environment are gravity, air resistance and air lift. As shown in Fig. 2, extral forces that acting on infinitesimal ds of arbitrary element ij are gravity, air resistance and air lift. v_p and r_p are respectively the velocity and coordinate vector of ds .

Figure 2. ANCF model extral force.

Aerodynamic force is obtained by the following formula

$$\mathbf{F}_p^D = \frac{1}{2} \rho_{air} C_D d |v_p|^2 ds \cdot \frac{1}{e_D} \quad (10)$$

$$\mathbf{F}_p^L = \frac{1}{2} \rho_{air} C_L d |v_p|^2 ds \cdot \frac{1}{e_L} \quad (10)$$

where ρ_{air} is air density, d is the diameter, C_d and C_L are respectively air resistance coefficient and air lift coefficient. $\frac{1}{e_D}$ and $\frac{1}{e_L}$ are respectively the direction vector of air resistance and air lift. So the virtual work done by external forces can be expressed as

$$\delta P_e = (\vec{G}_p + \vec{F}_p^D + \vec{F}_p^L) \delta \vec{r} \quad (11)$$

All above, the virtual work equation for element ij can be

$$\delta P_a + \delta P_s + \delta P_e = 0 \quad (12)$$

And then after analysis, dynamic equation of element ij is

$$-\ddot{W}^T M - KW + N^T (\vec{G}_p + \vec{F}_p^D + \vec{F}_p^L) = 0 \quad (13)$$

2 Semi-spring damper model

The whole space rope network is simplified to a multi-body system dynamic model, as shown in Figure 3. In the process of modeling, the elastic force and damping force of each rope segment is calculated. Then the aerodynamic force, gravity or other external forces are calculated. And at last, the dynamic equation of each node are set up.

Figure 3. Semi-springs damper model.

The tension of the rope between any two nodes is

$$T_{ij} = \begin{cases} f(l_{ij}) & l_{ij} > l_{ij}^0 \\ 0 & l_{ij} \leq l_{ij}^0 \end{cases} \quad (14)$$

where l_{ij} is the actual length of the rope segment ij and l_{ij}^0 is the original length. $f(l_{ij})$ is nonlinear force, and by experiment as shown in Fig.4, the force curve is measured as shown in Fig. 5.

Figure 4. Tensile testing machine.

Figure 5. Nonlinear stress curve.

For simplicity, taking the linear part of $f(l_{ij})$ for modeling, which is

$$f(l_{ij}) = k_{ij}(l_{ij} - l_{ij}^0) + c_{ij}\dot{l}_{ij} \quad (15)$$

Where k_{ij} and c_{ij} are equivalent elastic coefficients and equivalent damping coefficients of rope segments ij .

Figure 6. External force on s_{ij}

Similar to ANCF model, the air resistance and air lift are

$$F_n^D = \frac{1}{2} \rho C_D d |V_n^c|^2 l_{ij}^0 \vec{e}_D \quad (16)$$

$$F_n^L = \frac{1}{2} \rho C_D d |V_n^c|^2 l_{ij}^0 \vec{e}_L \quad (17)$$

Therefore, the kinetic equation of point i can be expressed as

$$m_i \ddot{\vec{r}}_i = \vec{T}_i + \vec{D}_i + \vec{F}_i + \vec{G}_i \quad (18)$$

Where $\vec{T}_i$ is the equivalent elastic force, $\vec{D}_i$ is equivalent damping force, $\vec{F}_i$ is Aerodynamic force, and $\vec{G}_i$ is gravity.

$$\vec{T}_i = \sum_{n \in R(i)} \vec{T}_n \quad (19)$$

$$\vec{D}_i = \sum_{n \in R(i)} \vec{D}_n \quad (20)$$

$$\vec{F}_i = \frac{1}{2} \sum_{n \in R(i)} \vec{F}_n \quad (21)$$

$$\vec{G}_i = \frac{1}{2} \sum_{n \in R(i)} \vec{G}_n \quad (22)$$

where $R(i)$ is the collection of rope segments that are connected to node i .

4 Ground test

In order to verify the dynamics model, the following experiment was designed: Using the quadrilateral tethered-net as shown in the Fig.7, and the four corners were respectively connected with a bullet weight of 0.5 kg. After the start of the experiment, the rope net was released from a high position. Then using the binocular measurement method to record the change in the spatial position of the four bullets.

Figure 7. Tethered-net with bullets.

Figure 8. Experimental framework.

The tethered-net is fixed to the release mechanism as shown in Figure 9, where 401 is the steering gear, 402 is the traction rope, 403 is pulley and 404 is the bolt. The pulley and the traction rope are used to transfer the change of the steering gear attitude to the latch. By controlling the changing shape of the steering gear by wireless controller, the mass block is released and then tethered-net freely falls..

Figure 9. Local amplification of the release mechanism.

In the absence of wind conditions, the movement of the net is shown in Fig.10 .

Figure 10. Experimental.

The spatial motion of each bullet is shown if Fig.11. And after extracting data, the area of the tethered-net changes with time are as shown if Fig.12.

Figure 11. The spatial motion of each bullet.

Figure 12. The area changes with time.

5 Simulation and analysis

Using ANCF model and semi-spring damper model to simulate the movement of the tethered-net. In order to be easy to observe, this article list shape contrasts of the mouth and diagonal ropes at several moments, as shown in Fig.13 and Fig.14.

Figure 13. ANCF.

Figure 14. Semi-spring damper.

After observing Fig.13 and Fig.14, it can be found that ANCF model can get more details of the rope than semi-spring damper model. At the same time, ANCF mode, which cost 7200s, is more computationally expensive than semi-spring model, which cost only 110s.

Comparing of the net-mouth area calculated by the two models with the experiment is shown in Fig.15.

Figure 15. Comparing of the net-mouth area.

The mean squared error of the ANCF model is 0.0115, and the value of the semi-spring damper model is 0.0134. The results from both methods show a good agreement with experiment. And the precision of ANCF model is higher.

6 Conclusion

This article established the aerodynamic Semi-spring damper model and ANCF model of the tethered-net system. And the results from both methods show a good agreement with experiment. The results indicate that the ANCF model is very suitable to describe the dynamics of a tethered-net. Furthermore, ANCF model is more capable of describing the flexibility of the net with fewer nodes than the conventional semi-spring damper model. However, it is more computationally expensive. Based on the comparison of single-step computational time, mass spring model is nearly 66 times faster than ANCF model.

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